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QUALITATIVE METHODS FOR ELICITING JUDGEMENTS FOR DECISION MAKING

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Multi-criteria decision analysis for nature conservation: A review of 20 years of applications

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Abstract

1. Multi-criteria decision analysis (MCDA) is a method to support decision-making, by exploring the balance between the pros and cons of different alternatives to accomplish a specific goal. It assists in framing decision problems, illustrating the performance of alternatives across criteria, exploring trade-offs, formulating a decision and testing its robustness. This paper provides a structured review of empirical applications of MCDA to nature conservation published in the scientific literature over the last 20 years. The paper aims at taking stock of past experiences, and comparing them with best practices and common pitfalls identified in the literature, to provide recommendations for better MCDA application to conservation.
2. The review follows the structure of a generalized MCDA process consisting of three key stages: (1) decision context and problem structuring, (2) analysis and (3) decision.
3. The search identified 86 papers that describe MCDA applications to a range of topics, including conservation prioritization and planning; protected areas management and zoning; forest management and restoration; and mapping of biodiversity, naturalness and wilder. The results show that, concerning problem structuring, a small percentage of the reviewed MCDA engaged stakeholders other than the authors in identifying alternatives and formulating criteria (15% and 35% respectively). Concerning the analysis, criteria assessment was adequately justified by the authors (47%), at times also by involving other stakeholders (22%). Weighting was performed in almost all applications, whereas criteria aggregation was mostly based on the weighted linear combination (63%). Sensitivity analysis was largely overlooked (57%). Concerning decision, 45% of the articles provided only an overall ranking or suitability of alternatives, while 22% included additional rankings according to specific criterion, and 8% further analyses and clustering of stakeholders' preferences.
4. The paper concludes by suggesting key elements of successful MCDA applications, including clear construction of the decision context; collaborative identification of alternatives and criteria that reflect the values at stake; adequate justification and communication of the methods for criteria assessment and weighting; reasoned choice of the criteria aggregation method, and comprehensive sensitivity analysis.

KEYWORDS

biodiversity conservation, criteria assessment, decision-making, multi-criteria decision analysis, stakeholders, weighting

1 | INTRODUCTION

Decision-making in nature conservation increasingly requires comparing alternatives to achieve multiple and competing goals, such as protecting habitats while addressing needs of vulnerable communities, and possibly fostering economic growth (e.g. Karlson, Karlsson, Mörtberg, Olofsson, & Balfors, 2016; Zhang et al., 2013; Zia et al., 2011). Conservation goals involve complex and spatially explicit biophysical, socio-cultural and economic issues, whose understanding necessitates appropriate methods of knowledge synthesis (Pullin et al., 2016) and stakeholder engagement (e.g. Etxano et al., 2015; Ianni & Geneletti, 2010). Alternatives include all types of options or courses of action to achieve a specific goal (Steinemann, 2001). They may comprise, for example, different locations and design for natural parks or restoration areas (Uribe, Geneletti, del Castillo, & Orsi, 2014; Van Elegem, Embo, Muys, & Lust, 2002), options for ecosystem management (Cordingley, Newton, Rose, Clarke, & Bullock, 2016; Jalilova, Khadka, & Vacik, 2012), plant species for reforestation (Reubens et al., 2011) or wildlife management units (García-Marmolejo, Escalona-Segura, & Van Der Wal, 2008).

Multi-criteria decision analysis (MCDA) is an effective knowledge synthesis method to support decision-making, by systematically exploring the pros and cons of different alternatives (Beinat & Nijkamp, 1998; Geneletti & Ferretti, 2015; Linkov & Moberg, 2012). It allows comparing alternatives against a set of explicitly defined criteria that account for the most relevant aspects in a given decision-making process. Operationally, MCDA supports structuring decision problems, assessing the performance of alternatives across criteria, exploring trade-offs, formulating a decision and testing its robustness. Multi-criteria decision analysis is particularly useful when reducing a multi-objective problem into a single-objective problem is either unfeasible or undesirable, especially in participatory settings involving diverse stakeholders with diverse objectives (Linkov et al., 2006). Criteria can be incommensurable, and expressed through different units of measurement: monetary values, number of new jobs, biophysical units, qualitative evaluations, etc. (Geneletti, 2010). The main strength of MCDA is that it allows combining the analytical performance of the alternatives with the preferences and priorities of stakeholders in a transparent and replicable fashion (French, Maule, & Papamichail, 2009).

For these reasons, MCDA has been increasingly used in conservation to support the identification of the most suitable alternative(s), by integrating factual information coming from surveys or modelling, with value-based information collected through stakeholder engagement (e.g. Nordström, Eriksson, & Karin, 2011; Strager & Rosenberger, 2006). Thus, MCDA is often integrated with other methods and tools, such as participatory approaches and Geographic Information Systems, as exemplified in Mustajoki et al. (2011) and Janssen, Knudsen, Todorova, and Hoşgör (2014). Participatory approaches include a wide range of methods—for example, Delphi technique (Mukherjee et al., 2015), focus groups (Comino, Bottero, Pomarico, & Rosso, 2014), face-to-face meetings (Pasqualini et al., 2011)—that aim at eliciting the values, preferences and knowledge of stakeholders (Mendoza & Prabhu, 2005). In order to be useful, MCDA and its integration with other methods and tools, need to be carefully designed and tailored to the specific context and decision-making process. In conservation, this has led to a variety of approaches and applications that, to the best of our knowledge, have never been systematically analysed and reviewed.

The aim of this paper is to provide a structured review of empirical applications of MCDA to nature conservation published in the scientific literature over the last 20 years. It adds to a more general review of MCDA applications in environmental sciences carried out by Huang, Keisler, and Linkov (2011) and its follow-ups by Cegan, Filion, Keisler, and Linkov (2017) and (Kurth, Larkin, Keisler, & Linkov, 2017). Particularly, this paper proposes a content-based review focusing on studies explicitly addressing nature and biodiversity conservation. Starting from a generalized MCDA process adapted from the literature, the review has two objectives. First, to take stock of past experiences by investigating how key stages of the MCDA process have been performed. Second, to compare these findings with best practices and common pitfalls identified in the MCDA literature, in order to provide recommendations for successful MCDA application in nature conservation.

2 | MATERIALS AND METHODS

Many MCDA approaches exist, which differ, inter alia, in terms of computational complexity, level of stakeholder engagement, and time and data requirement. Belton and Stewart (2002) present a detailed analysis of the theoretical foundations of different MCDA approaches as well as their comparative strengths and weaknesses. Nevertheless, it could be argued that most approaches involve the three main stages of the generalized MCDA process shown in Figure 1 (based on Geneletti & Ferretti, 2015; Kiker, Bridges, Varghese, Seager, & Linkov, 2005), in which a key aspect is the involvement of different actors providing different types of input to the process. A brief description of this process follows; more details can be found in the cited literature.

The first stage of the MCDA process aims to establish a shared understanding of the decision context, and to structure the problem. Operationally, it includes definition of the objectives of the decision process, identification of possible alternatives to achieve them and formulation of explicit criteria to assess how each alternative contributes to achieving the objectives. Objectives and criteria, often organized in a hierarchical or network structure called value or decision tree, have to be complete, concise, operational, independent and understandable (see Gregory et al., 2012; Keeney, 1992).

The second stage is the actual analysis, broadly consisting of: criteria assessment, weighting, criteria aggregation and sensitivity analysis (see Belton & Stewart, 2002; Munda, 1995; Roy, 1996). Criteria assessment is the quantification of the performance of each alternative against each criterion defined in the first stage. Conceptually, it consists of two steps: providing "raw" information about the effects of each alternative on each criterion (e.g. through surveys or modelling); hence converting this information into a dimensionless scale of preference, that is, a dimensionless expression of the level of desirability of the alternatives (Geneletti, 2005a, 2005b). This second step should be

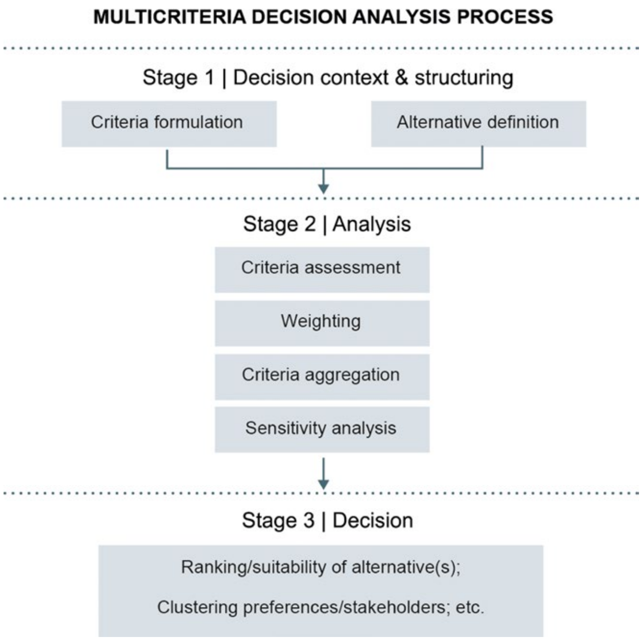

FIGURE 1 A generalized scheme of the mains steps of a multi-criteria decision analysis approach (based on Kiker et al., 2005; Geneletti & Ferretti, 2015)

based on inputs from relevant actors that can be gained using specific techniques, such as value functions (Beinat, 1997; Geneletti, 2004). Yet, not all MCDA techniques require these two steps to be performed separately. The analytic hierarchy process (Saaty, 1980), for example, approaches the issue indirectly, by asking the actors to make a pairwise comparison of alternatives against each criterion, then summarizing the preferences in a normalized matrix.

Weighting accounts for the different degree of importance of the criteria to the decision, and it refers to quantified preferences among possible outcomes for criteria from the perspective of decision-makers and/or stakeholders. A weight is a value assigned to a criterion that indicates its relative importance with respect to the other criteria under consideration (Malczewski, 1999). Several different techniques can be applied to obtain ordinal or cardinal weights, based on the judgements and perception about the relevance of the different issues at stake. Typical weighting techniques include trade-off (Keeney & Raiffa, 1976), analytic hierarchic process (AHP; Saaty, 1980), swing (Von Winterfeldt & Edwards, 1986), random (Janssen, 2001), extreme weights (Janssen, 2001) and expected value (Janssen, 2001).

Criteria aggregation refers to the application of a rule (e.g. an algebraic expression) to combine the outcome of criteria assessment and weighting and assess the overall performance of each alternative. Different MCDA approaches apply different rules. The simplest, and possibly the most widely used rule is the weighted linear combination. A ranking of the alternatives is one of several methods to display and summarize the results of the criteria aggregation. Last, sensitivity analysis explores the relationship between the output and the input of the process (Saltelli, Chan, & Scott, 2000), and it serves to test the robustness of the results considering the uncertainty factors related to all the steps of the MCDA process.

The third stage of the MCDA is where information from the previous stages is brought together, ultimately leading to the actual decision. This is, however, a rather complex, and difficult stage to investigate, especially relying only on peer-reviewed publications. In fact, we would expect the information provided by the latter to be more exploratory and less about an actual decision (e.g. with a firm commitment of resources). More specifically, peer-reviewed articles usually focus on the identification of the most suitable alternative(s) considering diverse perspectives, gaining a better understanding of how each factor contributes to the final ranking, or exploring alliances between different stakeholders. Therefore, in the review, we searched for such information as a proxy of the actual decision, investigating how decisions could be made based on the MCDA results, regardless of their quality and of their actual implementation (Keeney, 2002).

Operationally, the review was carried out using the framework in Table 1, composed of questions and associated interpretation keys, representing the generalized MCDA process. For each MCDA application, we first answered the review question with text extracts and notes from the article; then, we classified this information using the interpretation keys in Table 1. We thus investigated how the literature addressed the three main stages of the MCDA process, describing the techniques that have been used and level of involvement of different actors. Hence, we analysed these findings in the light of best practices and common pitfalls reported in the MCDA literature, to provide recommendations to future MCDA applications in nature conservation.

The selection of the studies was conducted through keyword search in the Scopus database (www.scopus.com). The search (concluded on October 17, 2016) included studies published between 1996 and 2016 that contain nature or biodiversity conservation and MCDA (or relevant acronyms and synonyms, including multi-criteria analysis and evaluation) in the title, abstract or keyword. We specifically aimed at identifying a set of studies classified by their own authors as explicitly addressing nature and biodiversity conservation. The Supporting Information provides details on the search queries.

The search resulted in a total of 774 articles. Of these, 48 were review articles that were excluded. After reading the title and abstract of the remaining 726 articles, the sample was narrowed down to 155, the rest being mostly unrelated to MCDA (e.g. using it as an acronym with different meaning in other fields). Following, based on a content analysis conducted on the entire documents to check relevance (i.e. to see whether they report an actual MCDA application in nature or biodiversity conservation), the sample was further reduced to 86 articles (numbered in the Supporting Information). While not exhaustive, this sample can be considered sufficiently large to gain a useful insight into empirical applications of MCDA in nature and biodiversity conservation. In the following section, the articles are referenced with square brackets according to their numbering in the Supporting Information.

3 | RESULTS

On average, six articles have been published yearly since 2002. As shown in Figure 2, the case studies were located in Europe (49%),

TABLE 1 The review framework

Question	Interpretation key
STAGE 1: Decision context and structuring	
Geographical region of and publication year.	Country in which the study area is located and year of publication
What is the objective of the decision-making process? What is the spatial extent of analysis?	Main objective of the MCDA process (may differ from the overall objective of the article). Spatial extent of the study area: less than 500 km^2, between 500 and 250,000 km^2, between 250,000 and 1,500,000 km^2, or above 1,500,000 km^2
Are alternatives identified? If yes, how?	0 = No, no pre-defined alternatives; 1 = Yes. Alternatives are already existing; 2 = Yes. Alternatives are identified/designed during the study solely by the authors; 3 = Yes. Alternatives are defined/designed during the study, with input from stakeholders
How are criteria formulated?	0 = Formulated by the authors; 1 = Formulated with input from other experts; 2 = Formulated with input from stakeholders (if yes, specify the engagement technique); 3 = Formulated with input from the general public (if yes, specify the engagement technique)
STAGE 2: Analysis	
How are criteria assessed (i.e. how is the performance of the alternatives converted from the original unit of measurement into a dimensionless preference scale)?	0 = Not described/not performed; 1 = Assessment performed by the authors without providing justification; 2 = Assessment performed by the authors with justification; 3 = Assessment performed based on input from experts or stakeholders
How is weighting performed?	0 = Not described/not performed; 1 = Weighting performed by the authors; 2 = Weighting performed by the authors through multiple weight sets; 3 = Weighting performed by involving experts or representatives of stakeholders; 4 = Multiple weighting performed by involving experts or representatives of stakeholders
Criteria aggregation	Decision rule applied to aggregate the performance of the alternatives across criteria
Sensitivity analysis	0 = Not mentioned/nor performed; 1 = By changing weights (if applicable, specify the technique adopted); 2 = By changing scores; 3 = By changing criteria assessment method; 4 = By changing criteria aggregation rule; 5 = Testing the robustness of the results by collecting general feedback from participants; 6 = Testing the robustness of the results by consulting additional data sources
STAGE 3: Decision	
What information is provided by the MCDA to support the final decision? (more answers possible)	0 = Overall alternative ranking or suitability; 1 = Partial ranking or suitability according to specific criterion included; 2 = Multiple ranking or suitability according to different perspectives; 3 = Analysis and clustering of preference/stakeholders

Asia (17%), North America (13%), Africa (9%), South America (6%) and Australia/New Zealand (6%). In total, the articles covered 41 countries; the most represented countries being Italy (thirteen articles), UK (seven articles), USA (six articles), followed by Iran (five articles), Australia, Mexico and Spain (four articles each), and Finland, France and Sweden (three articles each), and the remaining 31 countries covered by one or two articles.

3.1 | Decision context and structuring

Overall, the reviewed articles covered five broad and not mutually exclusive topics. Most of the articles addressed forest management and restoration (25%), conservation prioritization and planning (24%), and protected area planning and management (21%), while fewer dealt with mapping of biodiversity, wilderness and naturalness (8%). Finally, the remaining 11% of the articles addressed a diverse set of topics, ranging from siting of solar energy development in areas with low biodiversity value to designing railroad corridors minimizing biodiversity impacts. In terms of geographic extent, 56% of the case studies covered an area between 500 and 250,000 km^2 (i.e. regional extent) and 33% covered an area of less than 500 km^2 (i.e. local extent). Fewer studies, 7% and 5%, were carried out at national (between 250,000 and 1,500,000 km^2) and continental extent (above 1,500,000 km^2) respectively.

Concerning the definition of alternatives, 41% of the reviewed MCDA applications had no pre-defined alternatives (see Figure 3); this includes studies aimed at selecting sites of biodiversity value suitable for protection or restoration [e.g. 41; 71], supporting zoning of terrestrial and marine protected areas [e.g. 8; 23], and mapping biodiversity assets or habitat suitability [e.g. 77; 72]. About 24% considered already existing alternatives. For example, [26] prioritized 104 protected

FIGURE 2 Multi-criteria decision analysis applications described in the reviewed articles grouped by country (dots placed on the capital cities)

areas in Italy (that are part of the "Natura 2000", the world's largest coordinated network of protected areas) based on their significance for biodiversity; [9] analysed 744 vacant parcels in New York City to select those that could cost-effectively meet conservation goals; [43] considered five alternative land uses to compare their provision of ecosystem services. In 20% of the MCDA, alternatives were designed by the authors, applying: spatial MCDA to identify restoration sites [e.g. 45; 41], heuristic algorithms to identify additional conservation sites [e.g. 18; 20] or forest modelling to simulate different management scenario [e.g. 56; 57; 58]. Finally, in 15% of the cases, the alternatives were defined together with stakeholders; for example, [52] involved local communities to identify woody species for restoration in Ethiopia, [24] defined protected area management scenarios in a participatory fashion in Greece, while [54] involved stakeholders in identifying potential areas for forest restoration in Argentina.

About criteria selection, in 49% of the MCDA the authors formulated the criteria without input from stakeholders (see Figure 5 and Supporting Information). They mostly relied on literature reviews to justify the selection of the criteria. In fewer cases, reference to legislation was made, such as the European Union Directives on Habitats, Birds and Strategic Environmental Assessment [2; 18], national action plans [59] or previous projects [40]. In 16% of the MCDA, experts other than the authors were involved, for example, through Delphi techniques [e.g. 25], focus groups [e.g. 73] and face-to-face meetings [e.g. 51]. In 27% of the MCDA, also stakeholders' representatives were involved, mainly thorough workshops [e.g. 13; 24; 28; 40; 46; 50; 58], interviews [e.g. 22; 29; 36] and focus groups [e.g. 26; 80; 83]. Finally, 8% of the MCDA included larger groups of stakeholders, for example, through workshops [e.g. 27; 48], participatory meetings [e.g. 17; 30], consultations and open meetings [e.g. 53; 62], and household surveys [6]. The participatory techniques used to involve experts and stakeholders in the criteria formulation are illustrated in Figure 4.

3.2 | Analysis

Concerning criteria assessment, in 21% of the articles the authors performed it (e.g. applying mathematical functions or direct assessment) without providing any further justification of the approach [e.g. 50; 75], whereas in 47% a justification was also included [e.g. 46; 49]. About 22% involved stakeholders in defining the criteria assessment method [e.g. 53; 58]. On the other hand, 10% of the reviewed MCDA partially overlooked the criteria assessment by avoiding the step related to the conversion into a dimensionless preference scale [e.g. 29; 40].

Weighting was not considered by 2% of the MCDA [e.g. 41; 77], while in 26% and 17% the authors themselves assigned a single [e.g. 20; 81] or multiple [e.g. 13; 63] sets of criteria weights respectively. In 24% and 17% of the MCDA applications, stakeholders were involved in assigning a single [e.g. 25; 65] or multiple [e.g. 28; 36] sets of criteria weights.

About criteria aggregation, the weighted linear combination was the most widely applied approach (63%), followed by AHP/analytic network process [e.g. 48; 40], and by the multi-attribute value theory [e.g. 47; 78]. Other approaches included the Novel Approach to Imprecise Assessment and Decision Environments (NAIADE) [e.g. 24; 32], Ordered Weighted Average [e.g. 1; 10], PROMETHEE [e.g. 27; 46] and SMART [e.g. 52]. In 7% of the cases, more aggregation methods were combined [e.g. 82], and finally, 5% of the reviewed articles applied some ad hoc rules [e.g. 81].

Of the reviewed articles, 43% did not report about any sensitivity analysis. Among the others, the sensitivity analysis was mostly applied to the weights (19%) [e.g. 56; 76], and only in fewer cases the scores (6%) [e.g. 28; 73], the aggregation rule (3%) [e.g. 32; 82] and the assessment method (1%) [11]. In 15% of the MCDA, it was performed by changing two factors of the above [13; 60] and in 5% three factors [70; 80]. Finally, in 5% of the articles the robustness of the results was

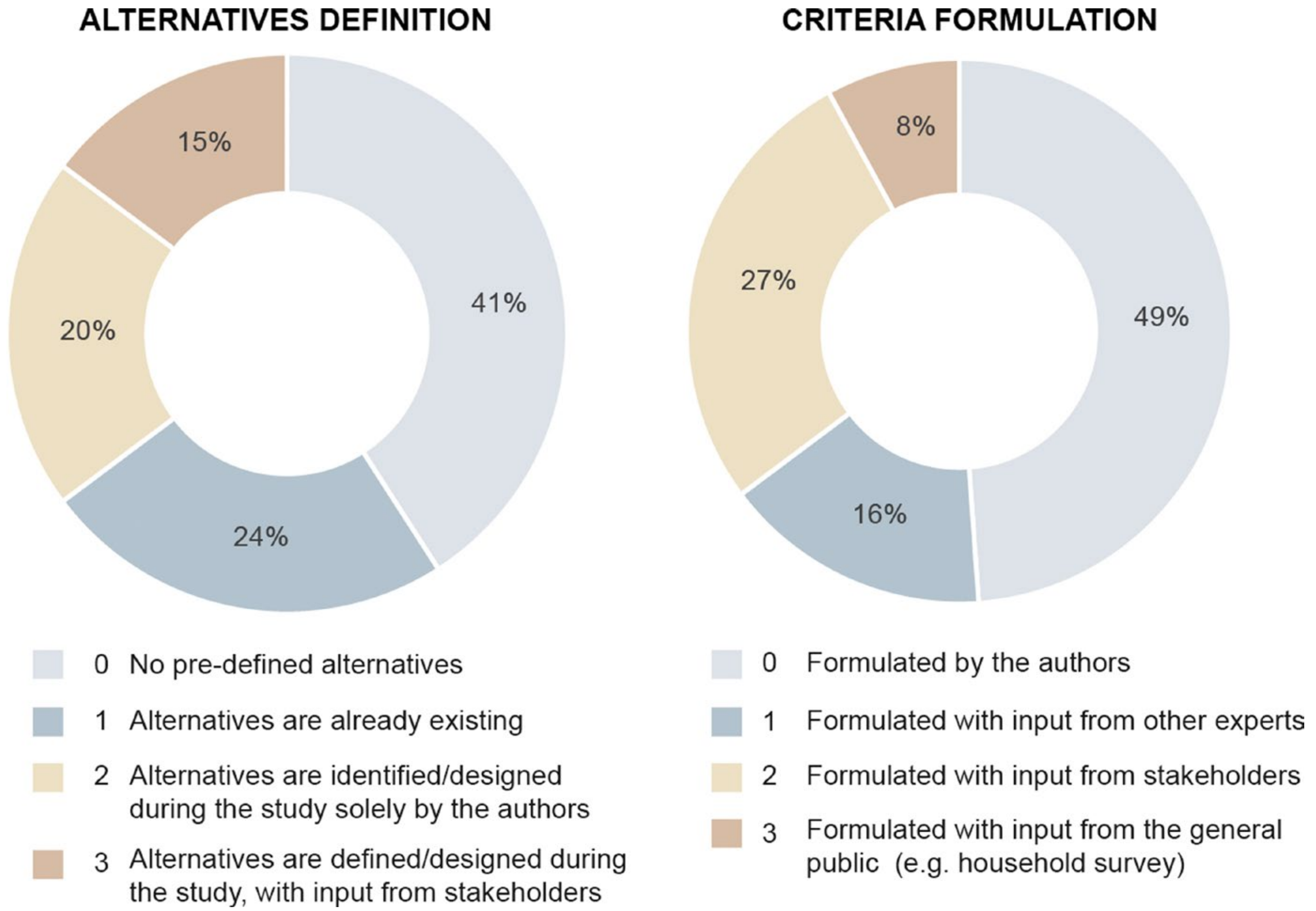

FIGURE 3 Identification of alternatives and formulation of criteria in the reviewed articles

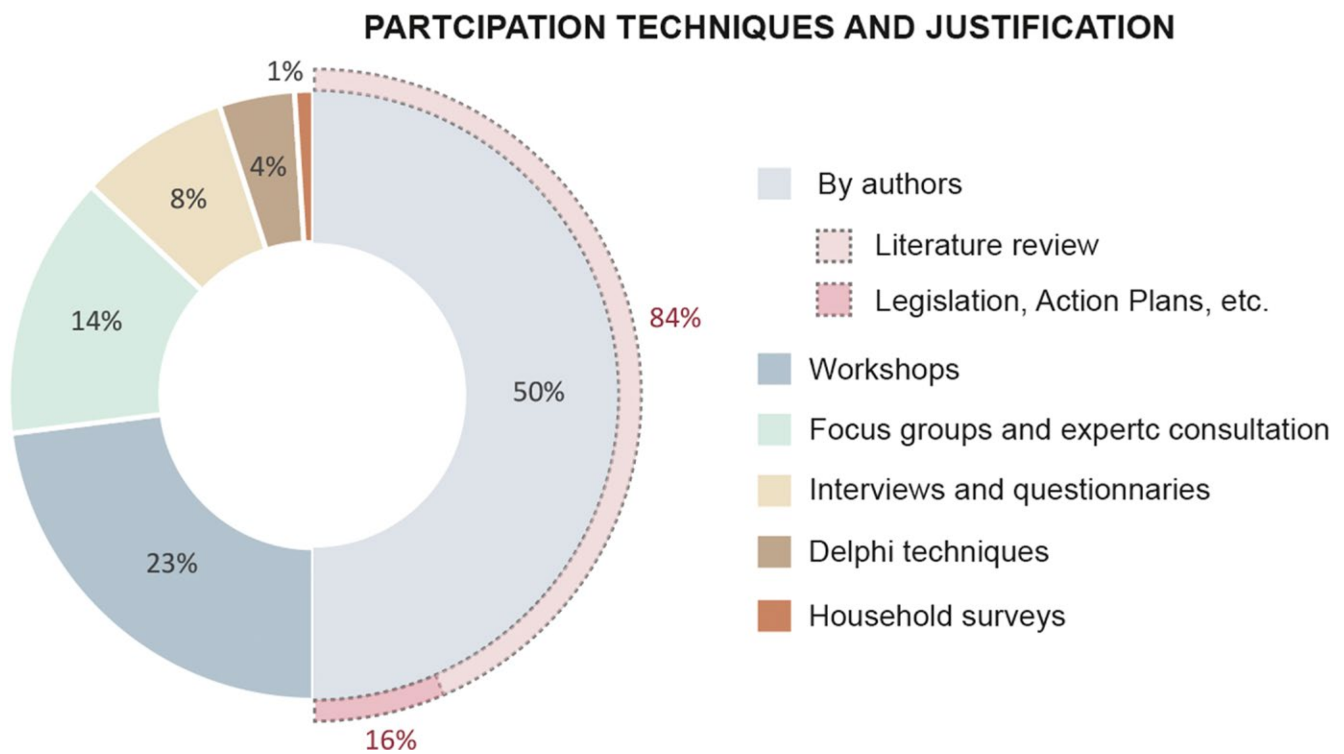

FIGURE 4 Participation technique and justification of the formulation of the criteria in the reviewed articles

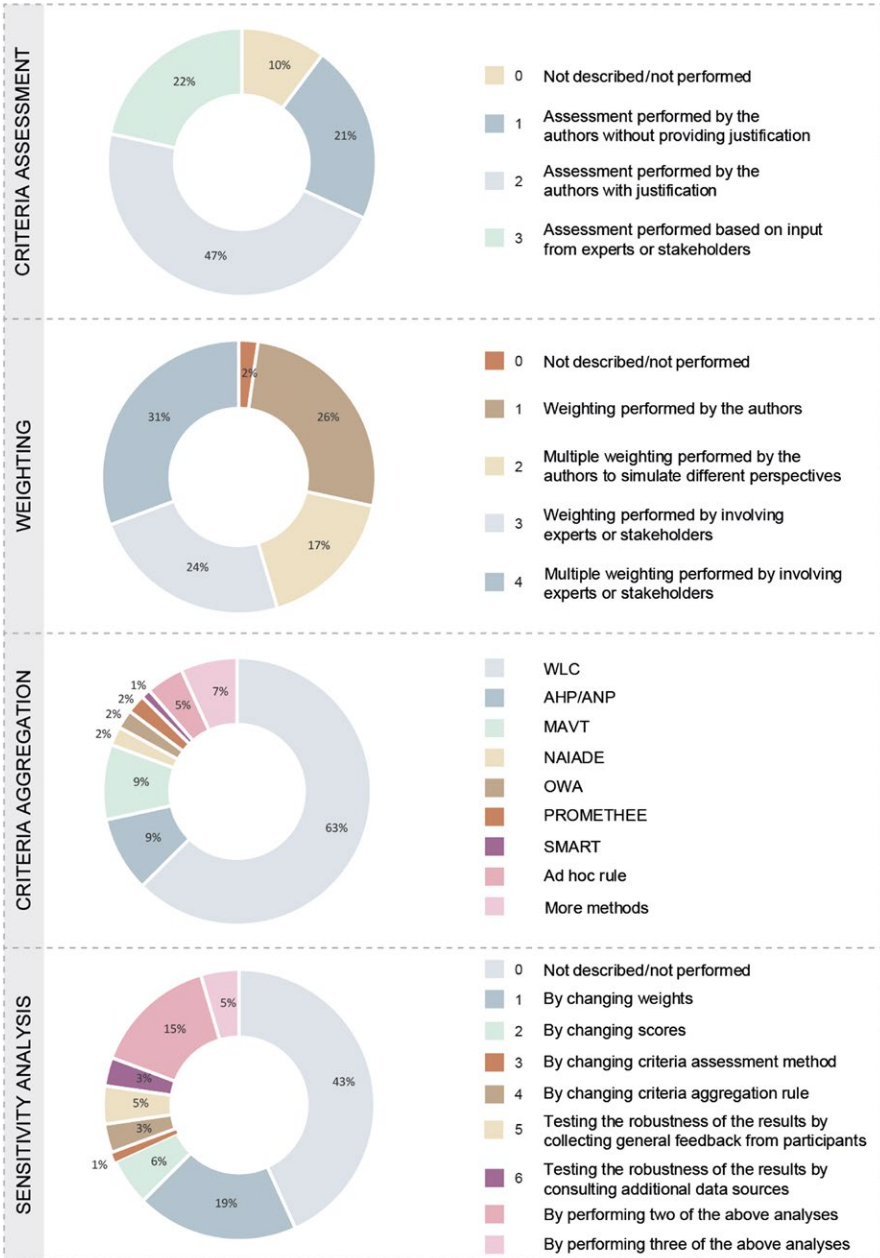

FIGURE 5 Analysis conducted in the reviewed articles

tested by collecting feedback on the MCDA results [e.g. 14; 79], and in 3% by consulting additional data sources [e.g. 68; 86]. Figure 5 summarizes the analysis in the reviewed articles (see also the Supporting Information).

3.3 | Decision

Almost half of the reviewed MCDA applications only provided an overall ranking of the alternatives or an overall suitability [e.g. 11; 12]; while 22% also included partial rankings or suitability [e.g. 2; 5]. Fewer articles (15%) reported multiple rankings, reflecting different perspectives [e.g. 13; 44], and 8% performed analysis and clustering of the preferences of stakeholders [e.g. 47; 68]. Only few articles included more information to support decision-making. For example, [73; 78] provided multiple overall, and partial suitability results; [86] presented both partial rankings as well as an analysis of the preference of the stakeholders; finally, [36] reported multiple rankings, together with an analysis of the different stakeholders' preferences. Figure 6 shows the analyses of the type of information provided in the articles to support decision-making (see more details in the Supporting Information).

4 | DISCUSSION

This review of MCDA applications to nature conservation adds to the more general review of applications within the environmental discipline carried out by Huang et al. (2011), which considered peer-reviewed papers published from 1990 to 2009, as well as to two follow-up studies by Cegan et al. (2017) and (Kurth et al., 2017). The latter studies in particular applied text mining to analyse large numbers

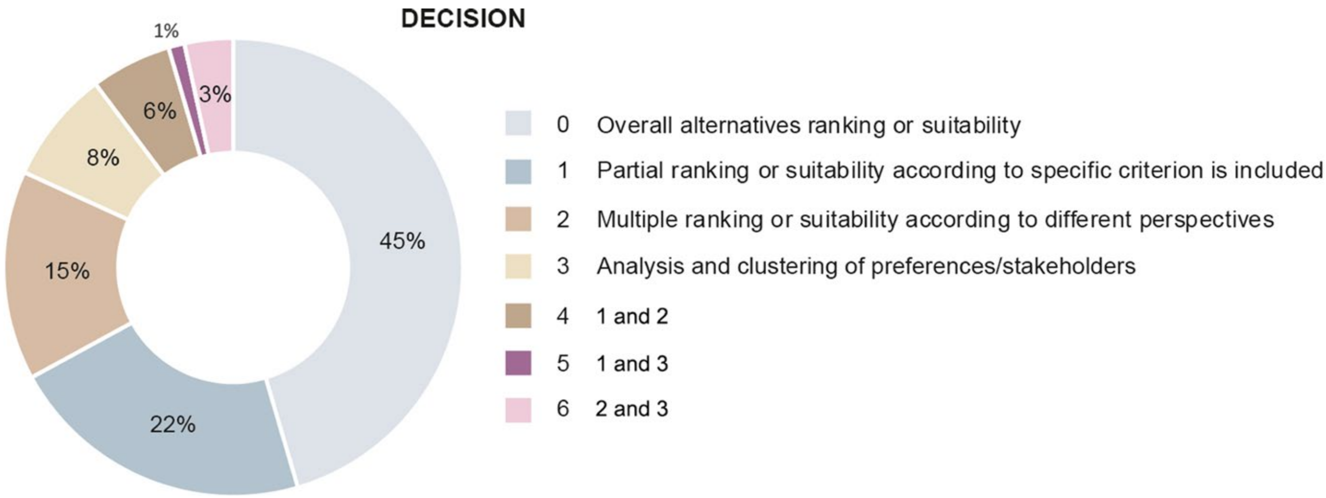

FIGURE 6 Classification of the articles based on the type of information provided to support decision-making

of MCDA applications, both in general and with respect to some major governmental agencies in the USA. The peculiarity of our study is that it applies a content-based review, focusing on a narrower set of articles classified by their own authors as explicitly addressing nature and biodiversity conservation. The review was carried out based on the generalized MCDA process described in Section 2.

We analysed 86 peer-reviewed articles presenting empirical application of MCDA to nature conservation. While not exhaustive, the sample was, however, assumed sufficiently large to gain a good insight into the application of MCDA in nature conservation, and to allow investigating the three main stages of the MCDA process. Future content-based reviews could widen the sample, for example, considering additional keywords such as "structured decision-making" (Gregory et al., 2012).

In the following sub-section, we discuss our findings in the light of MCDA best practices and common pitfalls, providing recommendations for more effective applications in conservation.

4.1 | Decision context and structuring

Structuring should be an iterative learning process that aims to enhance the understanding of the problem, and to recognize the values and preferences at play (Bana e Costa & Oliveira, 2002). Mustajoki et al. (2011) and Ferretti and Pomarico (2013), for example, refer to Keeney's (1992) value focused approach, illustrating the creative process to define a decision problem, articulate value trees and create relevant alternatives. As Keeney (1992) puts it, the values of stakeholders should be at the core of the decision-making, given that having explicit values makes it easier to define objectives, generate possible alternatives, compare them, and communicate and negotiate the results. Achieving a meaningful participation of the key actors is an important aspect, crucial also for increasing the acceptance of the final outcome of the MCDA (Gamper & Turcanu, 2007).

Nevertheless, only a relatively small percentage of the reviewed articles engaged stakeholders in identifying alternatives and formulating criteria (15% and 35% respectively). This confirms that, also in conservation decision-making, limited or poor problem structuring remains a common pitfall of MCDA applications, despite it has been shown to affect stakeholders' preferences, and ultimately the final decision (e.g. Tversky & Kahneman, 1981). The hierarchical arrangement of criteria deserves special attention, given that it affects stakeholders' perception of the problem, and their capability to actually deal with it (see, for example, Retief, Morrison-Saunders, Geneletti, & Pope, 2013; Weber, Eisenführ, & von Winterfeldt, 1988).

Objectives and criteria must be chosen to fit the problem according to stakeholders' concerns rather than to conform to any standardized expert-based hierarchy or criteria. There are no formal guidelines to indicate how a problem should be structured, and for most problems in conservation decision-making, an unambiguous correct structure does not exist. However, a good structure could be simply defined as: "[the] one that reflects a clear, logical and shared point of view about how the many [objectives and] criteria that may be relevant to a MCDA assessment can be brought together into coherent groups, each of which addresses a single component of the overall problem" (DCLG, 2009, p. 34). For example, a good structure avoids excessive and unbalanced number criteria for different objectives. Moreover, it is important that a representative set of alternatives is considered, which includes all alternatives that are relevant for the stakeholders (Janssen et al., 2014).

In this respect, it is worth noticing that existing frameworks, such as the Common International Classification of Ecosystem Services (Haines-Young & Potschin, 2013), could help to structure the objectives during or after an initial round of stakeholder involvement to define the problem. More in general, prior to the selection of objectives and criteria, there ought to be a problem definition step aimed at identifying a decision question along with relevant decision-makers, stakeholders and topic experts, ideally facilitated by an expert on participatory decision analysis (see, for example, Thorne et al., 2015).

4.2 | Analysis

Criteria assessment is a key phase in a successful MCDA (Beinat, 1997; DCLG, 2009). Our results show that in most MCDA applications (47%), the authors properly justified the step of criteria assessment, often by involving other stakeholders (22%). Ferretti and Comino (2015) is a good example of involvement of diverse actors (i.e. park authorities, residents, tourist, entrepreneurs and researcher) to formulate and validate value functions through focus groups. However, in some of the studies (e.g. Lu, Shen, & Chiau, 2014), criteria assessment was partially overlooked, for example, by considering only measurable, quantitative criteria (e.g. distance, extension, etc.), but without any further conversion into a dimensionless preference scale.

Weighting was well-addressed in the reviewed MCDA applications: the majority of the articles considered either single or multiple sets of weights, often defined together with stakeholders; only in few articles (2%) was weighting overlooked. Moreover, as compared to other steps of the MCDA process, weight elicitation emerged as the step in which stakeholders' preferences were included more straightforwardly.

A lack of understanding of the meaning of weights, and of the way they may affect results is nevertheless a potential pitfall in MCDA. Particularly, when techniques based on weighted linear combination are used, weights do not have an absolute or intrinsic meaning (van Herwijnen, 1999). Rather, they express how many units of a given criterion we are willing to sacrifice in order to gain one unit of another criterion. Therefore, weights need to be handled with care, and the correct information about their meaning and implications needs to be conveyed to the actors involved (see Choo, Schoner, & Wedley, 1999). For example, to derive weights, Ianni and Geneletti (2010) applied a 3-point scale pairwise comparison, which means that each criterion can be equally important, slightly more important or strongly more important than the criterion it is being compared to. This simplified 3-point scale approach was considered more appropriate than the more traditional 7- or 9-point scales because of the mostly qualitative nature of the criteria and the varied fields of expertise of the assessors (e.g. indigenous community members).

Indeed, a good practice is to test the consistency of the judgements expressed by stakeholders involved in the assignment of weights. This could be done by calculating a consistency ratio to measure how consistent the judgements have been relative to large samples of purely random judgements (Saaty, 1980). Accordingly, if the ratio is much in excess of 0.1, the judgements are untrustworthy given they are too close to randomness and the exercise should be repeated. In our sample of studies, consistency checks on weights was performed only in 14% of the cases. Among these, Schwenk, Donovan, Keeton, and Nunery (2012) argued that checking the consistency ratio of the respondents helped stakeholders to discuss and redefine preferences. Habtemariam and Fang (2016), on the other hand, arguably accepted a lower consistency threshold (0.2) with respect to stakeholders from various ministries involved in zoning of a marine protected area; while Derak and Cortina (2014), stated that they used a software (i.e. PriEsT) to computationally resolve consistency issues involving 38 stakeholders. Finally, Marre et al. (2016) gave respondents a possibility to revise inconsistent judgements.

Criteria aggregation, by combining weights and scores to derive overall values of each alternative across all criteria, is a crucial MCDA step leading to the final ranking of the alternatives. Our results show that the most applied algorithm was the weighted linear combination, generally preferred because of its straightforwardness, intelligibility by stakeholders and computation ease. Yet, only few articles explicitly mentioned that weighted linear combination is appropriate only if the criteria are mutually preference independent. Among these, Ferretti and Comino (2015) noted that independence between attributes should be fulfilled, and checked it with participants in a focus group. Similarly, Mustajoki et al. (2011) and Karlson et al. (2016) clearly assumed the adopted criteria to be mutually preferentially independent (as in Keeney & Raiffa, 1976). Geneletti (2007) tested for correlation among criteria, in order to avoid the use of correlated criteria that may cause redundancy and double counting, and generate inconsistent results.

Furthermore, weighted linear combination is a compensatory method, i.e. poor performance on some criteria can be compensated by better performance on other criteria. Thus, in particular decision contexts, the application of a different method or the introduction of thresholds to the degree of the compensability should be considered. An example of this is provided in Orsi and Geneletti (2010): to extract the most suitable areas for reforestation, the authors first identified two sets of criteria related to the need for restoration, and to its feasibility; accordingly, for each set of criteria, they set two different threshold values to be used prior to the weighted linear combination. Thus, they proposed a rather transparent approach to explicitly avoid undesired trade-offs.

Sensitivity analysis is essential for testing the robustness of the results considering the uncertainty factors related to all the steps of a MCDA. Sources of uncertainty in decision processes include measurement and conceptual errors, limited knowledge about process, simplification and data scarcity, and, above all, different values and opinions of stakeholders. Sensitivity analysis can be done through a number of techniques (see, for example, Delgado & Sendra, 2004; Janssen, 2001). The most popular ones consider how possible changes in the weights and the scores affect the final ranking (Janssen, 2001). Alternatively, sensitivity can focus on the weight of a specific criterion, aiming at identifying reversal points where the rank order of two (or more) alternatives change.

Sensitivity analysis was overlooked by almost half of the applications in nature conservation, despite such analysis would have provided crucial information about the level of stability and trustworthiness of the MCDA results. On the other hand, 20% of the MCDA applications present good examples of detailed analysis, combining several techniques. Moreover, two rather unconventional ways of performing sensitivity analysis were identified in the review: collecting feedback on the MDCA results from participating actors, and consulting additional data sources.

4.3 | Decision

Multi-criteria decision analysis ultimately aims to assist people in making decisions related to the objectives of the specific case study. It can serve diverse purposes in supporting decision-making, including providing structure to the debates between key actors, documenting the process of analysing the decision, making value judgements explicit, creating shared understanding and generating a sense of common purpose (DCLG, 2009, p. 111). These diverse purposes clearly emerged when examining individual studies in our review, as highlighted in the Supporting Information (Table S1, columns 5 and 12). In Riccioli et al. (2016), for example, the objective of the MCDA was to assess the effectiveness of existing environmental policies. To this end, their main results consisted of spatial clusters identifying areas with high biodiversity based on a set of criteria which were then crosschecked to see whether they overlap with existing protected areas in the region. Again, Marre et al. (2016) aimed to explore how different stakeholders value different aspects involving large-scale marine developments. To this end, they co-developed with stakeholders a hierarchical value structure for impact assessment of a hypothetical project, which they then used to explore, through a national survey, information preference of different types of stakeholders.

5 | CONCLUSIONS

A few common pitfalls in MCDA application emerged from this review of applications in nature conservation. Poor structuring, due to a not representative set of alternatives, to excessive and unbalanced number of criteria for different objectives, and perhaps due to scarce involvement of stakeholders, among others, is one. A successful MCDA application should start by clearly establishing the decision context, defining the purpose of the MCDA and identifying the main actors to be involved in the process. This is to be followed by a collaborative identification of an inclusive set of alternative options to meet the desired objective. The objectives, and related sub-objectives, have to be characterized by a set of criteria and indicators that reflect the values associated with the consequences of each option. Indeed, crucial to this end is a prior problem definition step, which includes identifying the decision question along with relevant decision-makers, stakeholders, and topic experts, ideally facilitated by a participatory decision analysis expert.

In the analysis stage, most of the reviewed articles did not explicitly discuss the rationale behind the criteria assessment step. This is a common pitfall of MCDA applications, in which little attention is given to how information about performance of each alternative is converted into a dimensionless scale of preference that expresses the level of desirability of that alternative. Adequate understanding about the implication of weights is another crucial aspect of a successful MCDA; however, in the reviewed articles, such information was often scarcely conveyed to the actors involved. A successful MCDA application should include an adequate description of the performance of each alternative option against each criterion. Furthermore, weights should be assigned to account for the different degrees of importance of the criteria to the decision, considering different stakeholders' perspective. Hence, a rule has to be applied to combine weights and scores in the overall values for each alternative. Examining the results of a MCDA in the light of its initial purpose is perhaps the most important step to assist people in making decisions. Finally, a successful MCDA application should always include a sensitivity analysis to examine the trustworthiness and robustness of its conclusions.

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AUTHORS' CONTRIBUTIONS

This article is the result of an equally shared research endeavour. Both authors conceived the ideas and designed methodology; hence, collected and analysed the data; and, finally, contributed critically to the drafts and gave final approval for publication.

DATA ACCESSIBILITY

The secondary data used in this paper consists of peer-reviewed articles retrieved in the Scopus database. Reference of the reviewed articles, together with some additional results, is provided in the Supplementary Information.

The Supplementary Information is archived in IRIS (see http://hdl.handle.net/11572/184016)—the Research Registry of the University of Trento—an Open Access institutional archive, whose full-text files are disseminated on the web and, following the publishers' policies in terms of Open Access, are freely accessible by web users (as well as specialized harvesters) without any password or other types of identification.

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Additional Supporting Information may be found online in the supporting information tab for this article.

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